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ANOMALOUS REFRACTION MAXIMA IN THE BIDIRECTIONAL TRANSMITTANCES OF ROUGHENED DIELECTRIC SURFACES

A. M. Smith

ARO, Inc.

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NOTICES

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FOREWORD

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ABSTRACT

Bidirectional distribution measurements were made of the plane-polarized radiant flux transmitted through roughened glass samples having various surface roughnesses. These monochromatic measurements were made in the plane of incidence as a function of the irradiance zenith angle. For an irradiance angle of 0 deg, it is found that as the surface roughness-to-wavelength ratio increases the relative binormal transmittance of the glass decreases and the bidirectional transmission distributions become more diffusing but do not approach a Lambertian distribution. For off-normal irradiance angles and surface roughness-to-wavelength ratios significantly greater than unity, the maxima in the bidirectional transmission distributions of the roughened glass samples occur at zenith transmission angles smaller than those prescribed by the macroscopic application of Snell's refraction equation to a transmitting surface system. These transmission extrema have been termed anomalous refraction maxima and their angular displacement from the Snell direction is found to increase with increasing surface roughness and zenith incidence angle. A formula is derived for the bidirectional transmittance in the plane of incidence and is used to quantitatively confirm the existence of the anomalous refraction maxima.

CONTENTS

ILLUSTRATIONS

SECTION I
INTRODUCTION

During the past few years there have been several detailed investigations of the bidirectional reflectance of roughened dielectric surfaces (Refs. 1 through 4). However, no comparable studies have been made of the bidirectional transmittance of such surfaces and, in fact, it is even difficult to find an explicit definition of this radiation property in the open literature (Refs. 5 and 6). In view of the considerable current interest in diffuse transmitting screens, it would be of significant value to have information on the bidirectional transmission properties of roughened dielectrics. Thus, the objective of the work reported here was to make an extensive investigation of the bidirectional transmittance of roughened dielectric surfaces. Since it is desirable to study these transmission characteristics in the absence of internal scattering effects, the dielectrics used were the roughened glass samples of Ref. 4. Detailed bidirectional transmittance measurements have been made for these roughened glass surfaces with all data being taken in the plane of incidence. These measurements of plane-polarized transmitted radiation were made for various surface roughnesses as a function of wavelength (in air) and the zenith incidence angle of the external irradiance. The results of the measurements for normal irradiance are used to show the effects of surface roughness-to-wavelength ratio on the relative binormal transmittance and bidirectional transmission distributions. For off-normal irradiance, the results show that the maxima of the bidirectional transmission distributions do not occur in the direction specified by Snell's law when the surface roughness is appreciably greater than the radiation wavelength. These transmission extrema are designated as anomalous refraction maxima because their angular locations in the refracted flux distributions deviate from those prescribed by Snell's law. The occurrence of anomalous refraction maxima in bidirectional transmittance distributions for roughened dielectrics is analogous to the off-specular peak phenomenon observed in bidirectional reflectance distributions (Refs. 2, 3, and 4). An analytical relation for the bidirectional transmittance of a randomly rough dielectric is formulated and used to substantiate the existence of the anomalous refraction maxima.

SECTION II
APPARATUS AND TEST SAMPLES

The bidirectional transmittance distributions for the roughened glass samples were measured using the apparatus shown schematically

in Fig. 1. This system has been described previously in detail (Ref. 7); it was essentially the same as that employed for the bidirectional reflectance measurements reported in Ref. 4, but had been modified for operation in the transmission mode. Briefly, mechanically chopped, unpolarized radiation was incident on the polished front surface of a glass disk at a zenith angle, Ψ, with a solid angle $\Delta\omega_i$ = 0.00022 sr (see inset, Fig. 1). The radiation transmitted through this polished surface was focused on the internal side of the glass sample's roughened face which was the rear surface. The radiant flux transmitted through the sample's rear surface in the direction defined by the zenith angle θ and the incidence plane was collected by a spherical mirror subtending a solid angle of $\Delta\omega_t = \Delta\omega_i$ = 0.00022 sr. This radiation was focused on the entrance slit of a monochromator after reflection from a plane first-surface mirror and transmission through a polarizer. It should be noted that the zenith incidence and transmission angles Ψ and θ were measured relative to the outward normals of the sample's front and rear surfaces, respectively.

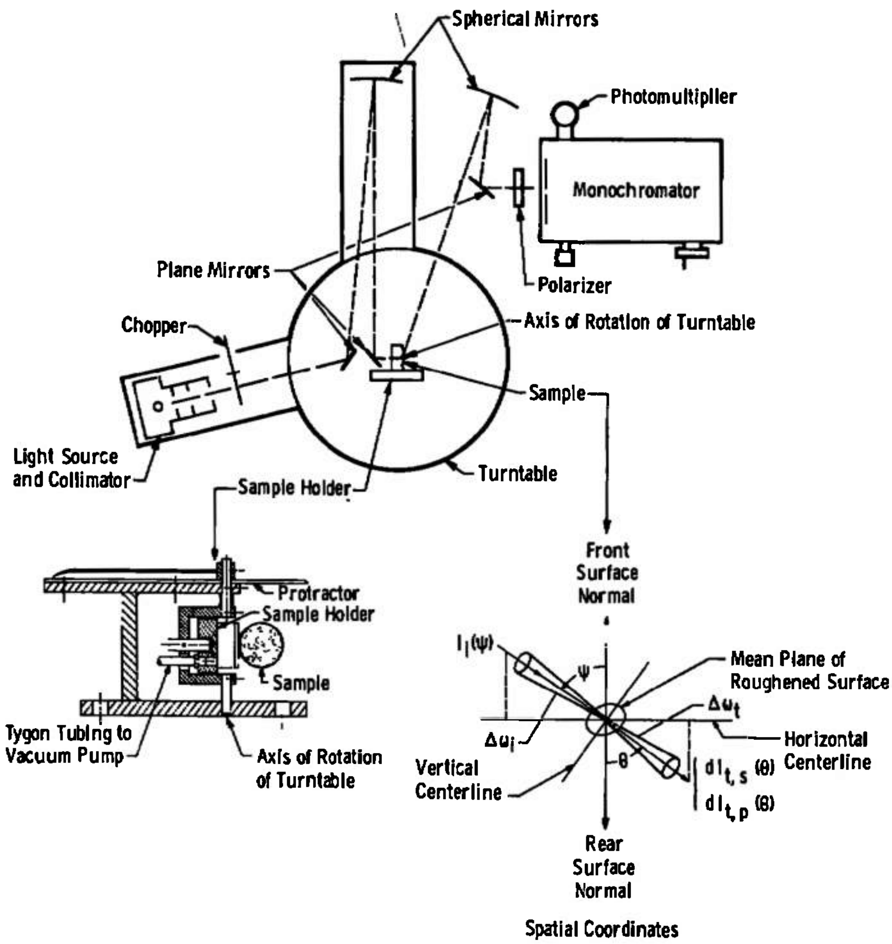

Fig. 1 Schematic of Experimental Apparatus

The five roughened glass samples used in this investigation were the same as those employed for the bidirectional reflectance measurements of Ref. 4. Hence, their rms mechanical surface roughnesses, σ_m, were 0.34, 0.63, 1.77, 3.35, and 5.22 μ. Of course, the black paint coating used on the polished side of each sample in Ref. 4 had to be removed before mounting the samples for transmission measurements. All samples had negligible absorption and internal scattering for visible wavelength radiation.

SECTION III
PROCEDURE

After alignment and calibration of the irradiation and detection optics, a roughened glass sample was mounted on the sample holder and the zenith angle of the incident radiation set to some desired value, Ψ. Then using the polarizer, the radiant flux transmitted through the sample's rear surface in a specific θ direction was alternately resolved into components polarized perpendicular and parallel to the plane of incidence. Each of these polarized radiation components was transmitted through the monochromator to the photomultiplier detector. A conventional strip-chart recorder was used to display the detector outputs after amplification and/or rectification and electronic filtering.

Once the above-described measurement was completed the turntable was rotated and the polarized radiant fluxes transmitted through the sample's rear surface in another θ direction were determined. This was subsequently done for values of θ ranging from -12 to 66 deg. Then the zenith incidence angle of the irradiance was set to a new desired value and the procedure repeated. Zenith incidence angles ranging from 0 to 50 deg were used. For normal irradiance ($\Psi = 0$), the distribution measurements were made for monochromatic wavelengths, λ, ranging from 0.4 to 0.7 μm. For off-normal irradiance ($\Psi \neq 0$ deg), distributions were only measured for $\lambda = 0.5\ \mu$m.

SECTION IV
DEFINITION OF BIDIRECTIONAL TRANSMITTANCES

In Fig. 1 (see inset), let $I_i(\Psi)$ denote the intensity of the unpolarized radiation incident on the glass sample through $\Delta\omega_i$ inclined at angle Ψ. Also, let $dI_{t,s}(\theta)$ and $dI_{t,p}(\theta)$ be the perpendicular (s) and parallel (p) polarization components of the transmitted radiant intensity

leaving the glass sample through $\Delta\omega_t$ inclined at angle θ in the plane of incidence. Then, for monochromatic radiation, one can define the s- and p-polarized bidirectional transmittances of the roughened glass as

$$\tau_s(\Psi,\theta) = dI_{t,s}(\theta)/I_i(\Psi)\cos\Psi\, d\omega_i/2\pi \qquad (1)$$

and

$$\tau_p(\Psi,\theta) = dI_{t,p}(\theta)/I_i(\Psi)\cos\Psi\, d\omega_i/2\pi \qquad (2)$$

where, since the incident beam is unpolarized, $I_i(\Psi)\cos\Psi\, d\omega_i/2$ is the irradiance for each polarization mode (s or p). Physically, this bidirectional transmittance definition can be interpreted as the ratio of the intensity transmitted by the roughened glass at angle θ in the plane of incidence, $dI_{t,s}$ or $dI_{t,p}$, to the intensity that would be transmitted in the same direction by a surface system which was perfectly transmitting and uniformly diffusing, $I_i(\Psi)\cos\Psi\, d\omega_i/2\pi$. Also, this definition is analogous to that currently in use for the bidirectional reflectance of diffusing surfaces. Of course, the analogy is necessary in order to satisfy the energy conservation principle as applied to transmitting surface systems.

SECTION V
EXPERIMENTAL RESULTS

Figure 2 shows how the surface roughness-to-wavelength ratio, σ_m/λ, affects the glass samples' bidirectional transmittance for normal (Ψ = 0-deg) incident radiation transmitted in the normal transmission direction, θ = 0 deg. This p-polarized binormal transmittance for the glass samples with a roughened rear surface, $\tau_p(\Psi = 0 \text{ deg}, \theta = 0 \text{ deg})$, is presented relative to $\tau_{p,O}(\Psi = 0 \text{ deg}, \theta = 0 \text{ deg})$, the p-polarized binormal transmittance for a glass sample having the rear surface polished. As mentioned previously, the front surface of all samples was polished. It can be seen in Fig. 2 that the relative binormal transmittance decreases rapidly with increasing σ_m/λ for values of σ_m/λ less than approximately 1.5. For σ_m/λ greater than 1.5, the relative binormal transmittance of the roughened glass decreases slowly with increasing σ_m/λ.

Figure 3 presents the bidirectional transmission distributions obtained for the roughened glass samples when the irradiance was normal (Ψ = 0 deg). The distributions given are for p-polarized radiation and are presented in the normalized form $\tau_p(\Psi = 0 \text{ deg}, \theta)\cos\theta/\tau_p(\Psi = 0 \text{ deg}, \theta = 0 \text{ deg})$ with σ_m/λ taken as a parameter. It is shown in Fig. 3 that the bidirectional transmission distributions become more diffusing with increasing σ_m/λ until σ_m/λ reaches a value of approximately 3.5. For

σ_m/λ equal to or greater than this value, the distributions do not change significantly with increasing σ_m/λ and hence their diffuseness is approximately constant. Note that the bidirectional transmission distributions do not approach a cosine distribution for any of the σ_m/λ values investigated. It should also be pointed out that the s-polarized distributions obtained for normal (Ψ = 0-deg) irradiance are not shown because they are essentially equal to the p-polarized distributions.

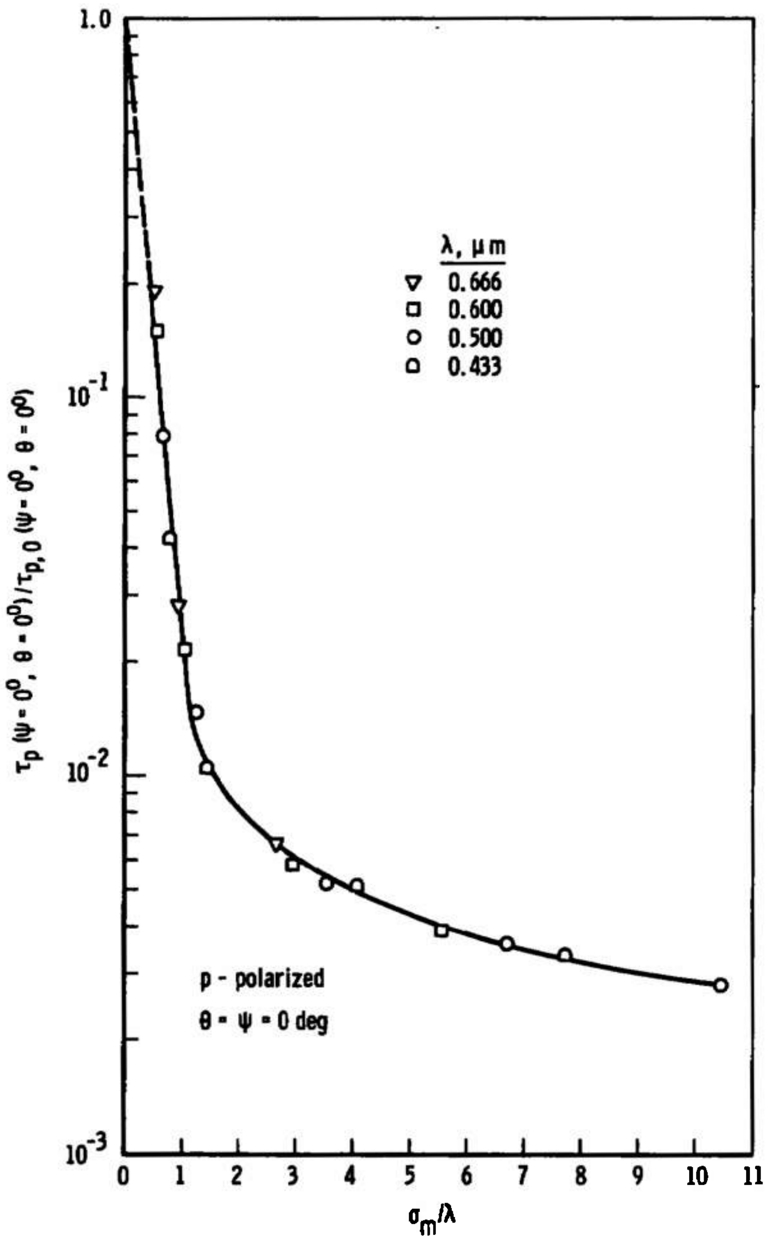

Fig. 2 Effect of Surface Roughness-to-Wavelength Ratio on the Relative Binormal Transmittance of Roughened Glass Samples for p-Polarized Radiation

The bidirectional transmission distributions obtained for the glass samples using irradiance angles Ψ of 0, 10, 20, 30, 40, and 50 deg are shown in Figs. 4, 5, and 6 for the samples with surface roughness σ_m of 0.63, 1.77, and 3.35 μ, respectively. In each figure graphs are given for both the s and p polarization components of the $\lambda = 0.5\ \mu m$ transmitted radiation. Note that the top graph is for s-polarized radiation and the bottom one is for p-polarized. As can be seen on the ordinate scale labels of the graphs, the distribution results are presented in the normalized form

$$\tau_s(\Psi,\theta)\cos\theta/\tau_s(\Psi,\Psi)\cos\Psi \text{ and } \tau_p(\Psi,\theta)\cos\theta/\tau_p(\Psi,\Psi)\cos\Psi$$

with the denominator of the ratios being the value of the numerator at the Snell refraction angle $\theta = \theta_S = \Psi$.

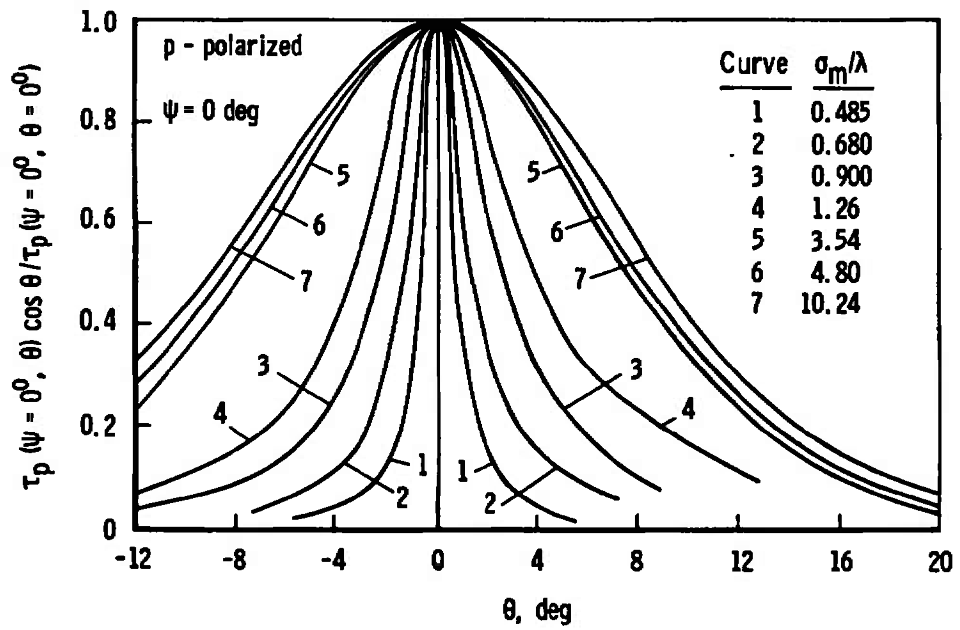

Fig. 3 Effect of Surface Roughness-to-Wavelength Ratio on the p-Polarized Bidirectional Transmission Distributions of Roughened Glass Samples for Normal Irradiance

It is shown in Figs. 4, 5, and 6 that the bidirectional transmission distributions of the glass samples for both normal and off-normal irradiance become more diffusing as the surface roughness, σ_m, increases relative to the radiation wavelength, $\lambda = 0.5\ \mu m$. It is also noted in Figs. 5 and 6 that for off-normal incidence angles the normalized bidirectional transmission distributions have values exceeding unity at zenith transmission angles immediately less than the Snell refraction angles, $\theta_S = \Psi$. Thus, the maxima of the bidirectional transmission distributions occur at zenith transmission angles smaller than

the Snell refraction angles. These transmission extrema will be referred to as anomalous refraction maxima since their angular locations deviate from those prescribed by the macroscopic application of Snell's refraction law to a transmitting surface system. As seen from Figs. 5 and 6, the anomalous refraction maxima occur in the bidirectional transmission distributions when the sample surface roughness, σ_m, is significantly larger than the transmitted radiation wavelength and the zenith irradiance angles are greater than 0 deg. When the sample surface roughness is smaller than the radiation wavelength, or even slightly greater as in Fig. 4, no anomalous refraction maxima occur for any angle of incidence.

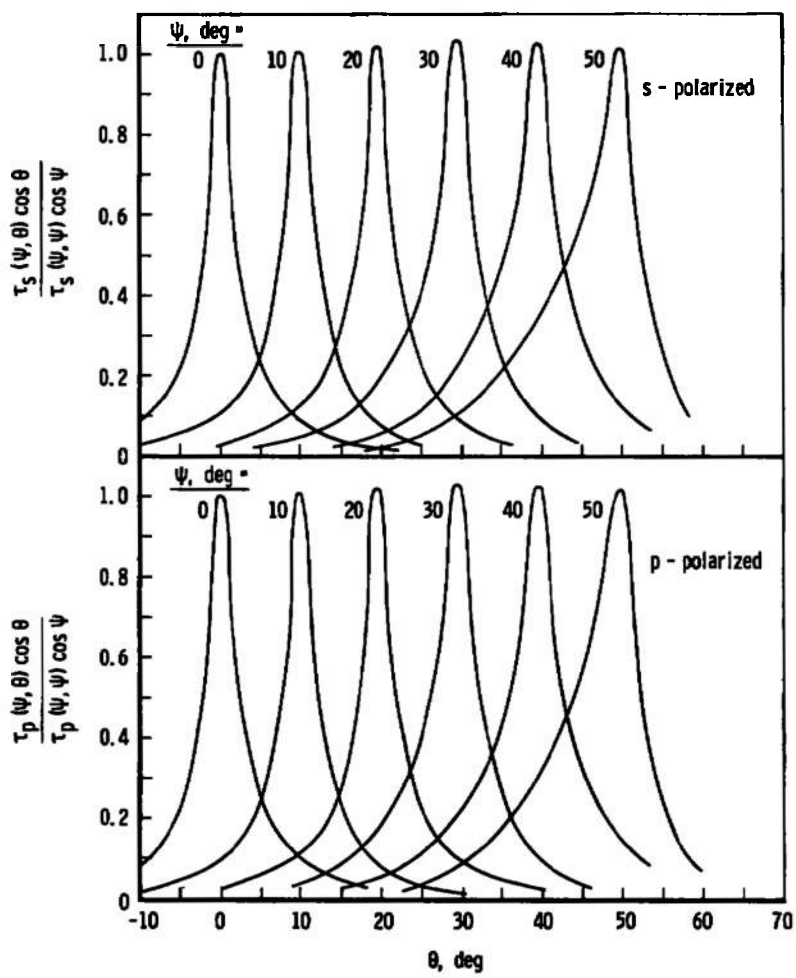

Fig. 4 Plane-Polarized Bidirectional Transmission Distributions of Roughened Glass Sample, σ_m = 0.63μ, λ = 0.5μm, Various Incidence Angles Ψ

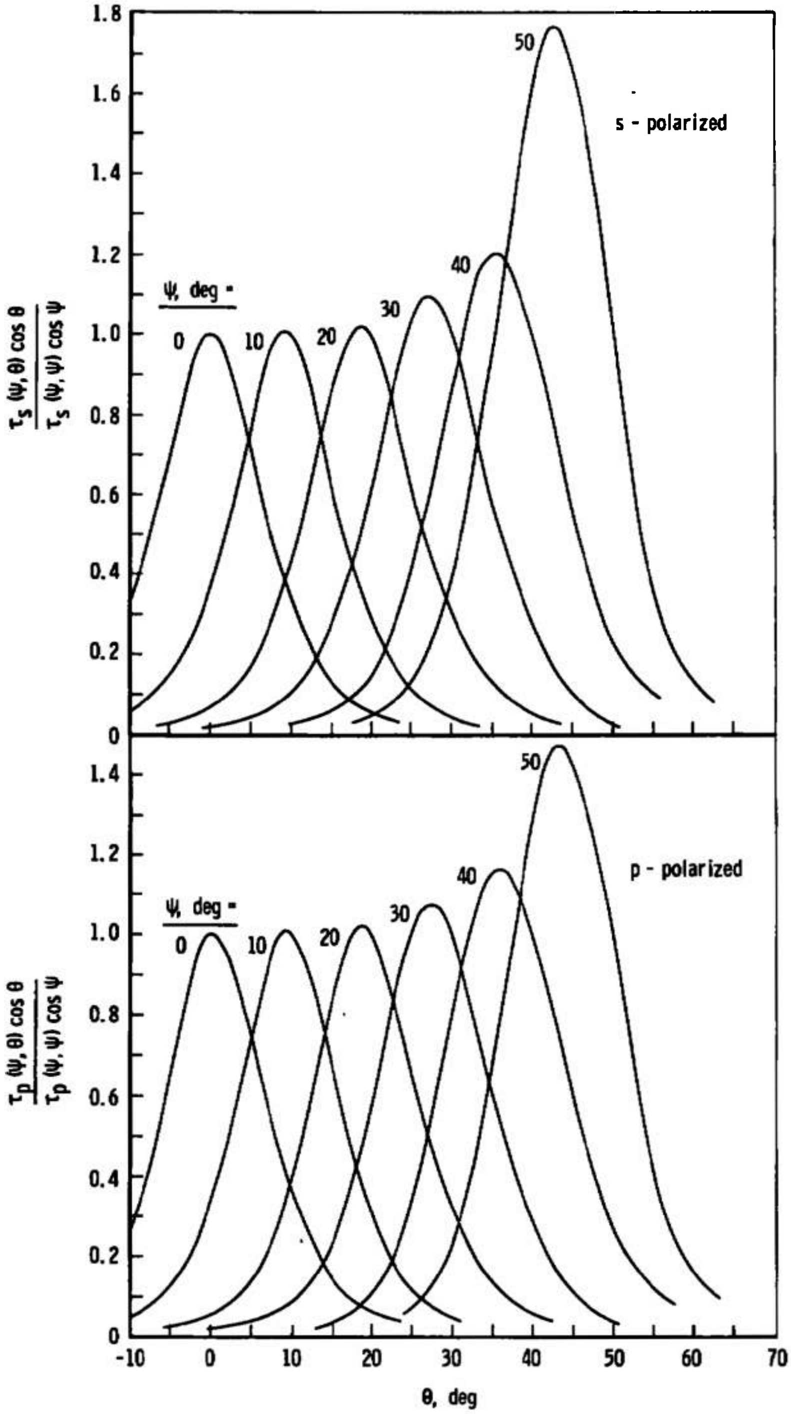

Fig. 5 Plane-Polarized Bidirectional Transmission Distributions of Roughened Glass Sample, σ_m = 1.77μ, λ = 0.5μm, Various Incidence Angles Ψ

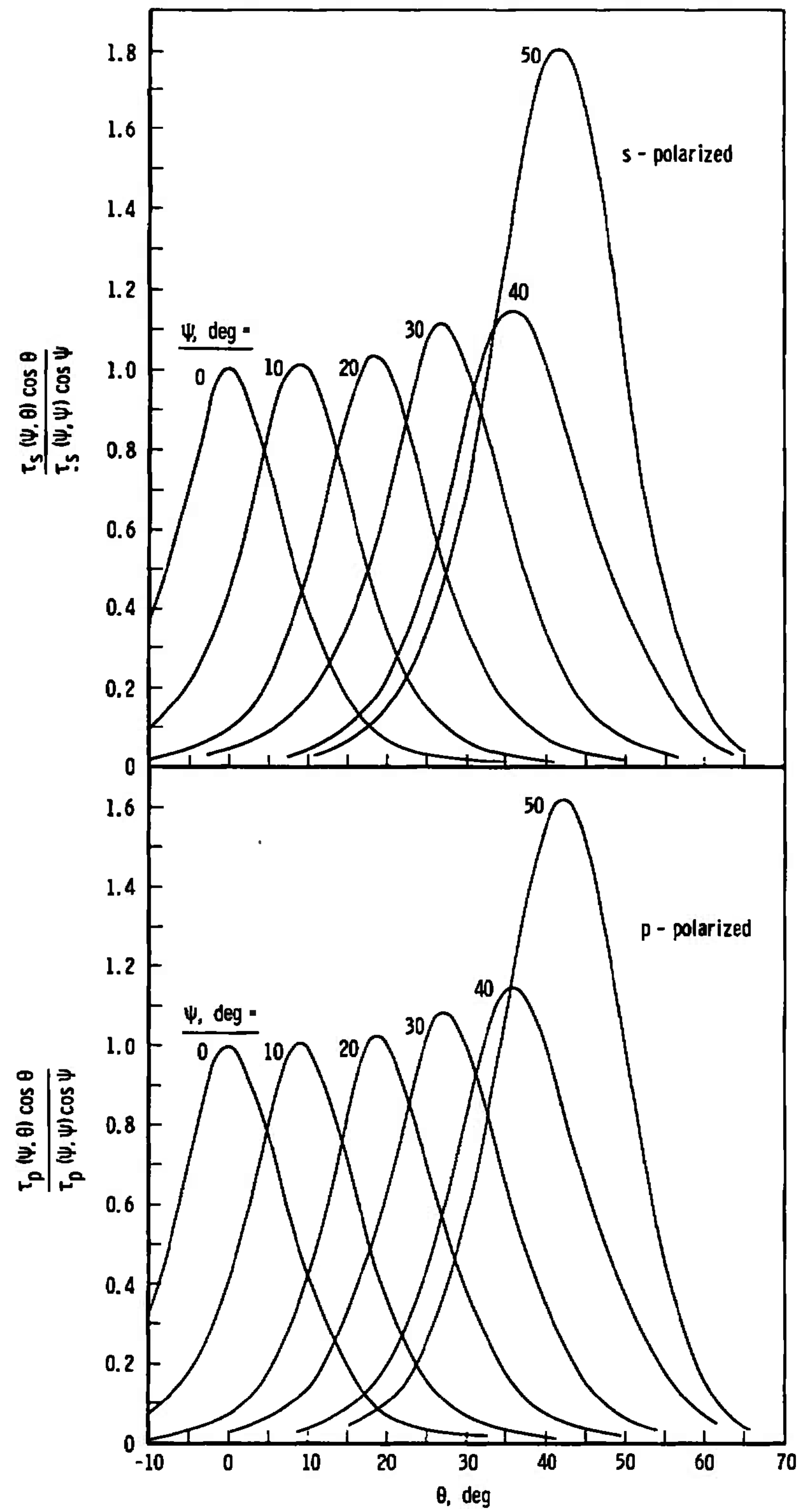

Fig. 6 Plane-Polarized Bidirectional Transmission Distributions of Roughened Glass Sample, σ_m = 3.35μ, λ = 0.5μm, Various Incidence Angles Ψ

Figure 7 shows the experimentally determined angular displacements (relative to the Snell direction, $\theta_S = \Psi$) of the anomalous refraction maxima in the p-polarized bidirectional transmission distributions for the roughened glass samples. These angular displacements, $\theta_m - \theta_S(= \Psi)$, where θ_m denotes the angular location of the maxima, are for a radiation wavelength of 0.5 μm and are displayed as a function of zenith incidence angle, Ψ, with sample surface roughness, σ_m, taken as a parameter. From the results shown, it is observed that when anomalous refraction maxima occur, their angular displacements relative to the Snell refraction angle will be greater for rougher surfaces and larger incidence angles. No results are shown in Fig. 7 for s-polarized radiation because the angular displacements of the anomalous refraction maxima in the s-polarized transmission distributions are equal to the angular displacements of the anomalous refraction maxima in the p-polarized distributions.

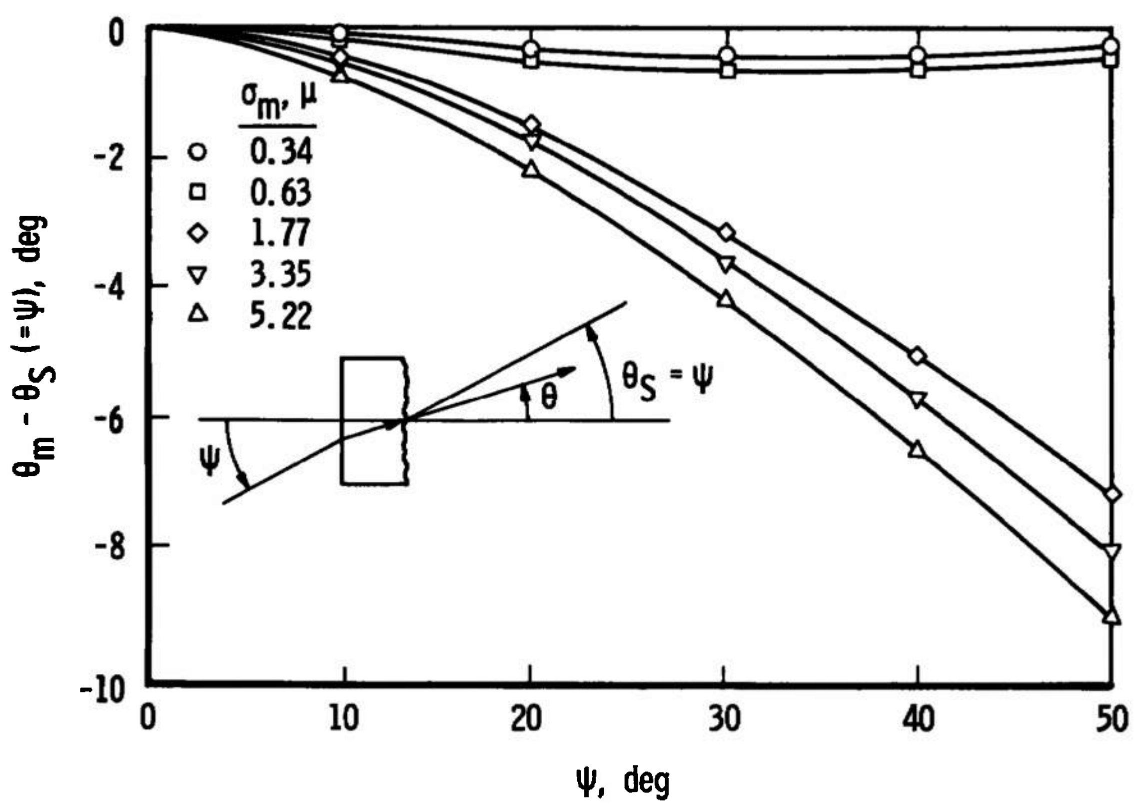

Fig. 7 Measured Angular Displacements (Relative to the Snell Direction) of Anomalous Refraction Maxima in the p-Polarized Bidirectional Transmission Distributions for Roughened Glass Samples, $\lambda = 0.5\mu m$, Various Surface Roughnesses σ_m and Incidence Angles Ψ

SECTION VI
THEORY AND COMPARISON WITH DATA

In order to theoretically confirm the existence of the anomalous refraction maxima, a simple analytical expression will be formulated for the bidirectional transmittance of the roughened glass samples in the plane of incidence. To begin, consider in Fig. 8 the intensity $I_i(\Psi)$ of the radiation incident externally on the smooth surface of the glass sample at angle Ψ with respect to the outward surface normal. Since this radiation is unpolarized, the incident radiant intensity for both the s- and p-polarization modes is $I_i(\Psi)/2$. Thus, from Fresnel and Snell's laws for the smooth surface, radiant intensity is transmitted into the glass sample in the direction $\eta = \sin^{-1}(\sin\Psi/n)$ with s- and p-polarized components $I_j(\eta) = T_j(\Psi, n)\, n^2\, I_i(\Psi)/2$, $j = s, p$. Here, n is the refractive index of the glass at wavelength λ with $T_j(\Psi, n)$, $j = s, p$ being the s- and p-polarized components of the Fresnel transmittance (Ref. 8). Now, as indicated in Fig. 8, the radiant intensity transmitted into the glass sample is contained within the differential solid angle $d\Omega_i$ inclined at angle η where $d\Omega_i = \cos\Psi\, d\omega_i/(n^2 \cos\eta)$. Thus, the s- and p-polarized components of the radiant flux density incident internally on the irradiated area $dA(\eta)$ of the roughened surface of the glass sample are $I_j(\eta)\cos\eta\, d\Omega_i$, $j = s, p$. These flux density components incident on $dA(\eta)$ are related to the external irradiance $I_i(\Psi)\cos\Psi\, d\omega_i$ by

$$I_j(\eta)\cos\eta\, d\Omega_i = T_j(\Psi,n) I_i(\Psi)\cos\Psi\, d\omega_i/2, j = s,p \tag{3}$$

Next, it is necessary to make several assumptions about the characteristics of the roughened surface of the glass samples. Since this surface is the same as that considered in Ref. 4, the same assumptions will be invoked. Hence, the surface is assumed to be isotropic and randomly rough with the surface heights, $\zeta(x)$ (see Fig. 8), having a Gaussian distribution and an rms value of σ. From this assumption it can be shown, as indicated in Ref. 4, that the slopes of the rough surface, $\zeta'(x) = \tan\alpha$, also have a Gaussian distribution.

$$w(\zeta') = \frac{1}{m(2\pi)^{1/2}} \exp\left(-\frac{\tan^2\alpha}{2m^2}\right) \tag{4}$$

Here m denotes the rms slope for the rough surface and α is the inclination angle of a local slope. Now, as shown in Fig. 8, α also is the angle between the normal to the local slope and the normal to the mean plane of the rough surface. The distribution of the angle α for a Gaussian-distributed surface can be obtained from Eq. (4) by standard transformation techniques and is

$$\underline{P}'(\alpha,m) = \frac{\sec^2\alpha}{m(2\pi)^{1/2}} \exp\left(-\frac{\tan^2\alpha}{2m^2}\right) \tag{5}$$

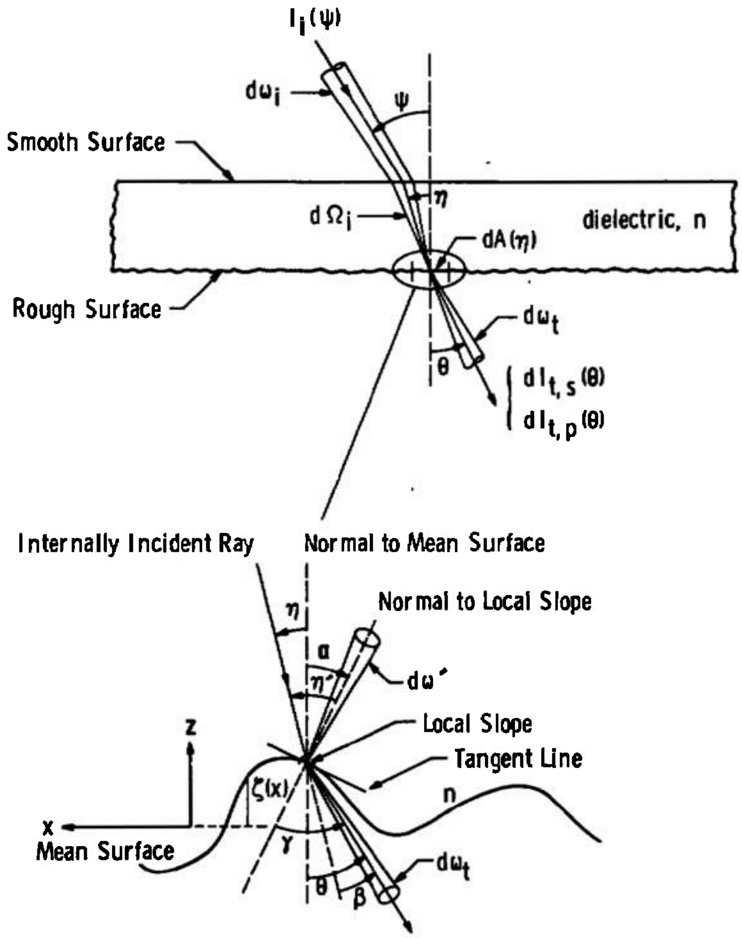

Fig. 8 Geometrical Optics of Radiation Transmitted through Roughened Dielectric Sample

Now, after assuming that the rough surface of the glass sample has a Gaussian distribution of surface heights, it is possible to derive a formula for the radiant flux transmitted through this surface into the plane of incidence. This derivation has been carried out using geometrical optics. Thus, the wavelength, λ, of the transmitted radiation is assumed to be small compared to the rms surface height, σ, of the rough surface. In addition, the basic transmission model for the rough surface assumes Snell refraction through the local surface slopes as shown in Fig. 8; i. e., $n \sin \eta' = \sin \gamma$ where $\eta' = \eta + \alpha$ and $\gamma = \theta + \alpha = \beta + \eta'$. Also accounted for is bistatic shadowing, which is the screening of local surface slopes by adjacent surface slopes interrupting the incident and singly transmitted radiant flux. The model does not account for the contribution to the transmitted radiant flux attributed to multiple interactions which occur when a ray encounters more than one slope before leaving the rough surface.

The results of this derivation for the s- and p-polarized transmitted fluxes $d\Phi_{t,j}$, j = s, p are

$$d\Phi_{t,j} = S(\eta,\theta,m)\,T_j(\eta+\alpha,1/n)I_j(\eta)\cos(\eta+\alpha)\,\underline{P}(\alpha,m)\,dA(\eta)d\omega'd\Omega_i,\ j = s,p \quad (6)$$

Here, $T_j(\eta + \alpha,\ 1/n)$, j = s, p are the s- and p-polarized components of the Fresnel transmittance for local incidence angle $\eta + \alpha$ and, following Refs. 9, 10, and 11, $P(\alpha,\ m)\ dA(\eta)\ d\omega'$ is the area of the local slopes in $dA(\eta)$ whose normals have directions within the differential solid angle $d\omega'$ inclined at angle α with respect to the mean surface normal. As mentioned previously, $P(\alpha,\ m)$ is the distribution function for the angle α and in this study is assumed to be given by Eq. (5). The $S(\eta,\ \theta,\ m)$ function in Eq. (6) is the bistatic shadowing relation for transmission through a normally (Gaussian) distributed rough surface and has the form

$$S(\eta,\theta,m) = S(\eta,m)\,S(|\theta|,m),\ |\theta| \leq \pi/2 \quad (7)$$

where, from Ref. 12,

$$S(\zeta,m) = \exp\left[-\frac{1}{4}\tan\zeta\ \mathrm{erfc}\left(\frac{\cot\zeta}{(2)^{1/2}m}\right)\right],\ \zeta = \eta,\theta \quad (8)$$

It should be noted that although the limits on θ in Eq. (7) are $-\pi/2 \leq \theta \leq \pi/2$, there is no singly transmitted ray for $\theta \leq -90 + \eta + \sin^{-1}(1/n)$ and $\theta \geq 90 + \eta - \sin^{-1}(1/n)$ because of total internal reflection.

Now combining Eqs. (3) and (6) with the relation between $d\omega'$ and $d\omega_t$

$$d\omega' = \frac{d\omega_t}{[1 - n\cos(\eta+\alpha)/\cos(\theta+\alpha)]^2\cos(\theta+\alpha)} \quad (9)$$

yields the following expressions for the transmitted s- and p-polarized fluxes

$$d\Phi_{t,j} = \frac{S(\eta,\theta,m)\,T_j(\eta+\alpha,\ 1/n)\,T_j(\Psi,n)\,I_i(\Psi)\cos\Psi\,d\omega_i\,\cos(\eta+\alpha)\,\underline{P}(\alpha,m)\,dA(\eta)\,d\omega_t}{2\cos\eta\cos(\theta+\alpha)[1 - n\cos(\eta+\alpha)/\cos(\theta+\alpha)]^2},\ j = s,p \quad (10)$$

Then from the definition of transmitted intensity, $dI_{t,j} = d\Phi_{t,j}/[\cos\theta\ d\omega_t\ dA(\eta)]$, j = s, p, and Eqs. (1) and (2), the theoretical formulas for the s- and p-polarized components of the roughened glass sample's bidirectional transmittance are

$$\tau_j(\Psi,\theta) = \frac{\pi S(\eta,\theta,m)\,T_j(\eta+\alpha,1/n)\,T_j(\Psi,n)\cos(\eta+\alpha)\cos(\theta+\alpha)\,\underline{P}(\alpha,m)}{\cos\eta\cos\theta[\cos(\theta+\alpha) - n\cos(\eta+\alpha)]^2},\ j = s,p \quad (11)$$

where η is related to Ψ by $\eta = \sin^{-1}(\sin \Psi / n)$ and α is functionally dependent on Ψ and θ through $\tan \alpha = (\sin \theta - \sin \Psi) / \left[(n^2 - \sin^2 \Psi)^{1/2} - \cos \theta\right]$. Note that $T_j(\eta + \alpha, 1/n)$, j = s, p in Eqs. (6), (10), and (11) is identically equal to zero for $|\eta + \alpha| \geq \sin^{-1}(1/n)$.

Equation (11) has been used to theoretically predict the experimental s- and p-polarized bidirectional transmission distributions for the $\sigma_m = 1.77\,\mu$ and $3.35\,\mu$ roughened glass samples of refractive index n = 1.51. As shown in Figs. 9 and 10, this was done for zenith irradiance angles of 10 and 50 deg using an rms slope, m, of 0.247 for the $\sigma_m = 1.77\,\mu$ sample (Fig. 9) and an rms slope of 0.280 for the $\sigma_m = 3.35\,\mu$ sample (Fig. 10). It is shown in Figs. 9 and 10 that the agreement between the theoretical (dashed) and experimental (solid) bidirectional transmission distributions is good for Ψ = 50 deg and excellent for Ψ = 10 deg. It is speculated that the agreement is not as good for the larger incidence angles because the multiple interactions contribution, which would increase with increasing incidence (and transmission) angles, has been neglected in the theoretical model. The good agreement between the analytical and experimental results in Figs. 10 and 11 quantitatively confirm the existence of the anomalous refraction maxima for off-normal incidence angles.[1]

Figure 11 presents a comparison between the angular locations θ_m of the anomalous refraction maxima of the experimental and theoretical bidirectional transmission distributions for the σ_m = 1.77- and 3.35-μ glass samples. These results were obtained from the s- and p-polarized transmitted flux distributions for incidence angles from 0 to 50 deg. As before, the theoretical flux distributions for the σ_m = 1.77- and 3.35-μ samples were obtained using rms slopes of 0.247 and 0.280, respectively. It is observed from Fig. 11 that there is excellent agreement between the experimental (solid) and theoretical (dashed) curves for the angular locations of the anomalous refraction maxima of both the s- and p-polarized distributions. This is shown to be true for both samples at all angles of incidence. Note that Fig. 11 also shows a comparison between θ_m and the Snell refraction angle θ_S.

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[1]In passing, it is noted that anomalous refraction maxima also should occur in the bidirectional transmission distributions when the irradiance (Ψ) and transmission (θ) directions are interchanged; i. e., when the glass sample is irradiated on the roughened side. However, the anomalous refraction maxima occurring for this sample orientation would be expected to lie at transmission angles greater than the Snell refraction angle. This has been confirmed theoretically using the analytical model presented earlier in the section.

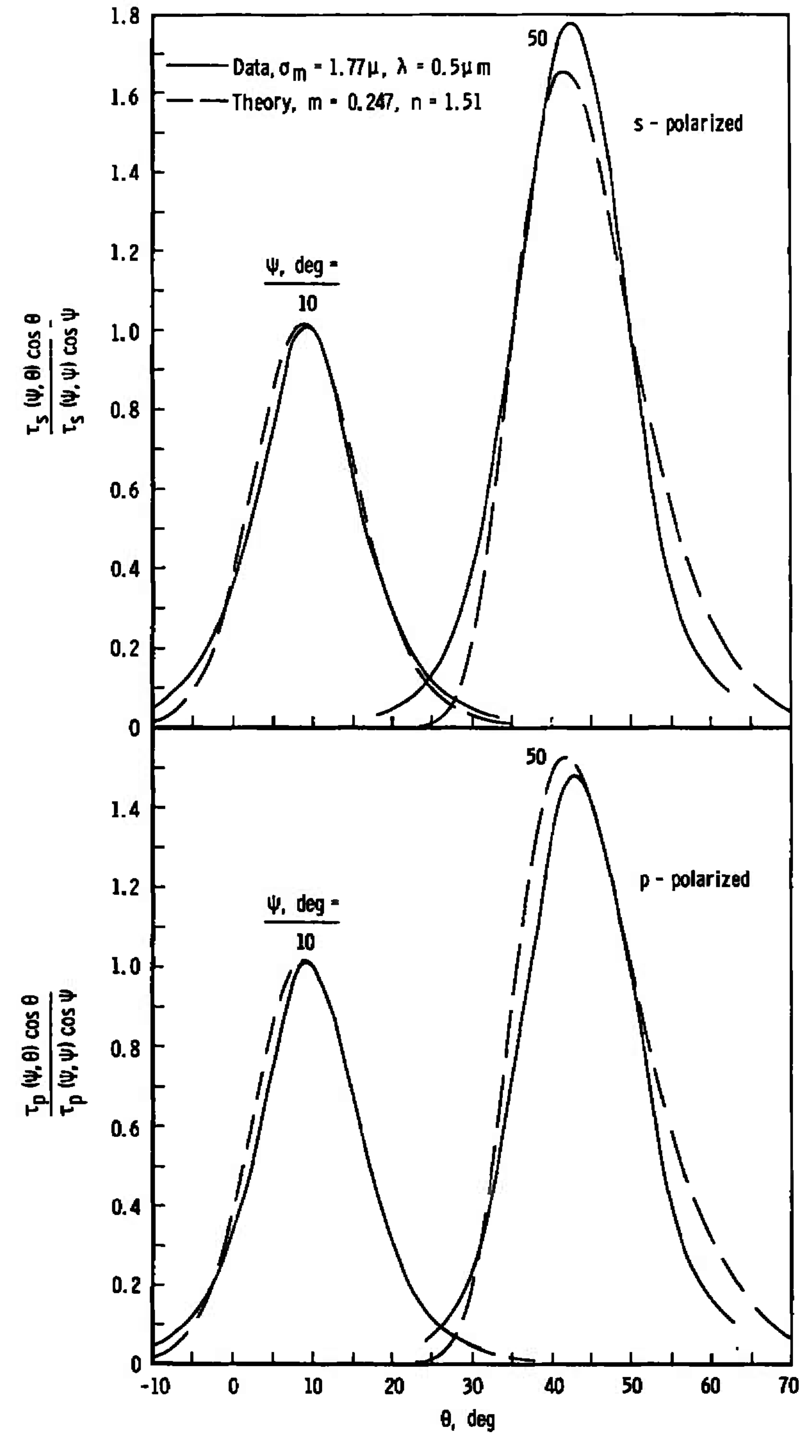

Fig. 9 Comparison between the Theoretical and Experimental Plane-Polarized Bidirectional Transmission Distributions of the σ_m = 1.77μ Roughened Glass Sample for Incidence Angles of 10 and 50 deg

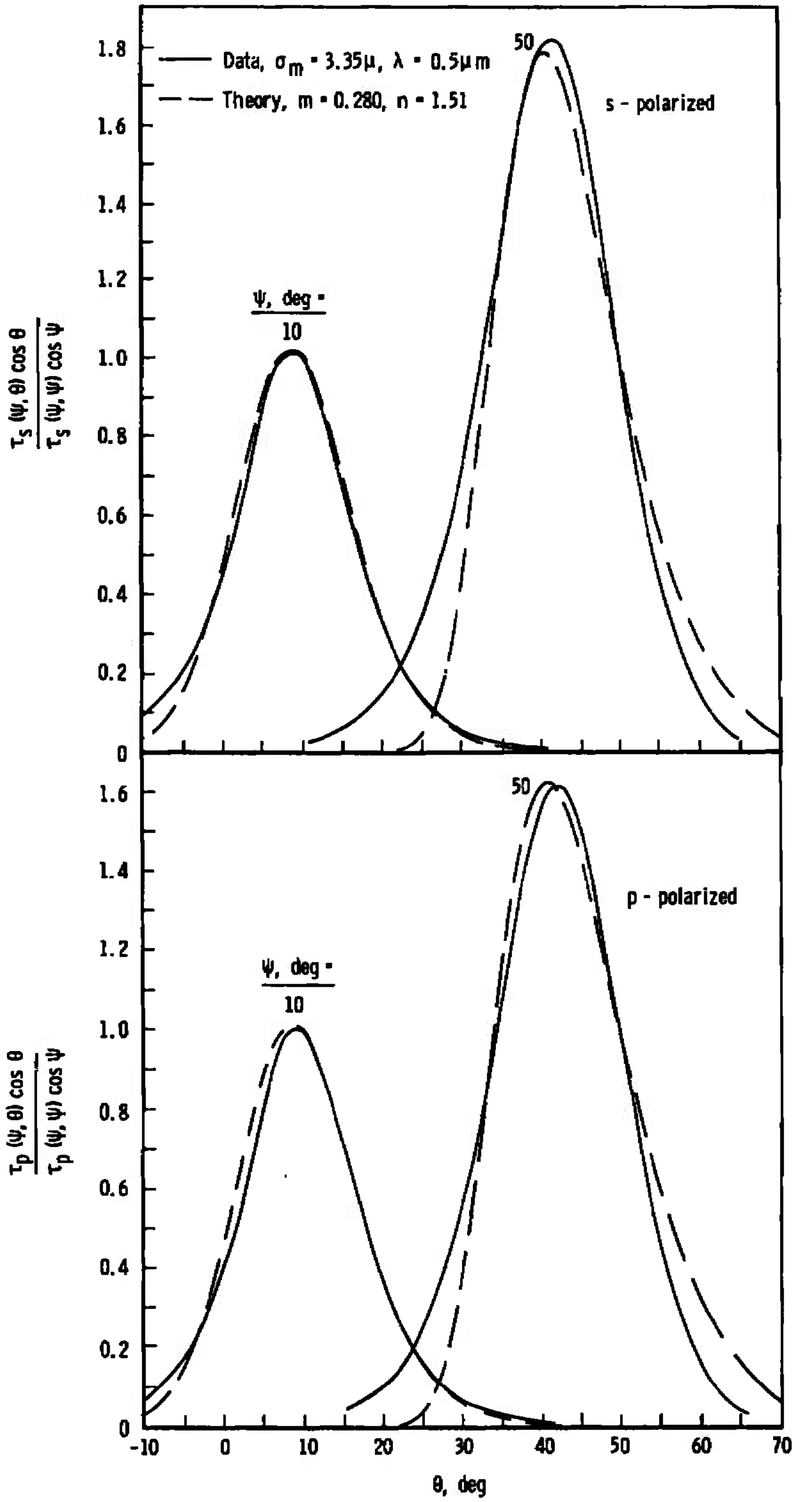

Fig. 10 Comparison between the Theoretical and Experimental Plane-Polarized Bidirectional Transmission Distributions of the σ_m = 3.35μ Roughened Glass Sample for Incidence Angles of 10 and 50 deg

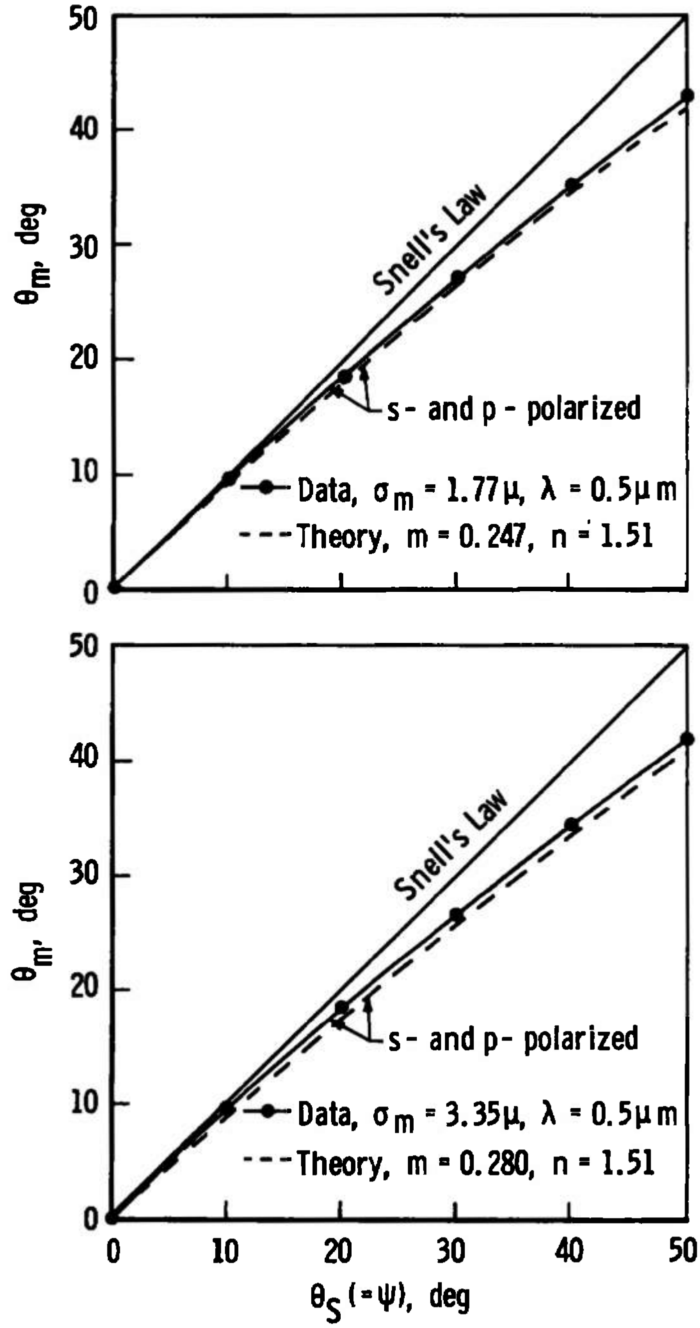

Fig. 11 Comparison between Angular Locations of the Anomalous Refraction Maxima of Theoretical and Experimental Plane-Polarized Bidirectional Transmission Distributions for the σ_m = 1.77 and 3.35μ Roughened Glass Samples with Various Incidence Angles Ψ

In Fig. 9 for the σ_m = 1.77 μ glass sample, the rms slope value yielding the best visual agreement between the experimental and theoretical bidirectional transmission distributions was equal, as it should be, to the slope value that gave the best agreement between the theoretical and experimental bidirectional reflection distributions for this sample in Ref. 4, m = 0.247. In Fig. 10 for the σ_m = 3.35-μ sample, the rms slope which gave the best agreement between the experimental and theoretical bidirectional transmission distribution was m = 0.280. Figure 12 shows that this slope value also yields excellent agreement between the theoretical and experimental (Ref. 4) bidirectional reflection distributions for the σ_m = 3.35-μ sample. Here $\rho_s(\Psi, \theta_r)$, $\rho_p(\Psi, \theta_r)$, and $\rho(\Psi, \theta_r)$ are the s-polarized, p-polarized, and mixed bidirectional reflectances, respectively, with Ψ and θ_r being the zenith incidence and reflection angles (see inset, Fig. 12). Note that $\rho(\Psi, \Psi)$ is the value of $\rho(\Psi, \theta_r)$ at the specular reflection angle, $\theta_r = \Psi$ = 20 deg.

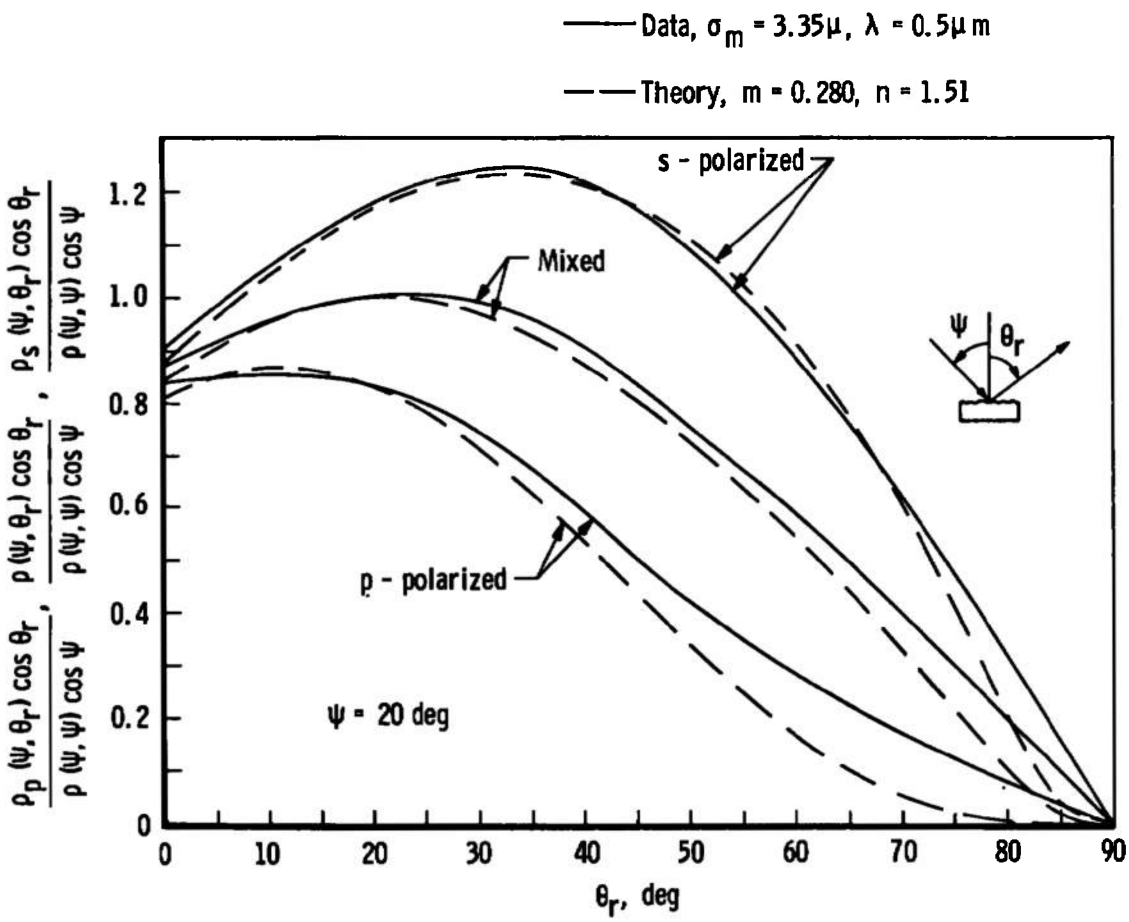

Fig. 12 Comparison between the Theoretical and Experimental Plane-Polarized Bidirectional Reflectance Distributions of the σ_m = 3.35μ Roughened Glass Sample for an Incidence Angle of 20 deg

SECTION VII
CONCLUSIONS

From the experimental and analytical results presented in the previous sections, it can be concluded that anomalous refraction maxima occur in the plane-polarized bidirectional transmission distributions for roughened glass samples. These anomalous refraction maxima occur when the zenith irradiance angle is greater than 0 deg and the rms mechanical surface roughness of the glass sample's roughened surface is appreciably larger than the wavelength of the transmitted radiation. The angular displacement of these anomalous refraction maxima from the Snell direction is observed to increase with increasing incidence angle and surface roughness. It is also concluded that as the surface roughness-to-wavelength ratio increases the relative binormal transmittance of the glass sample decreases drastically and the bidirectional transmission distributions become more diffusing but do not approach a uniformly diffuse distribution. Finally, it is further concluded that the analytical model formulated for the anomalous refraction maxima is realistic and yields theoretical results which are in good agreement with the experimental data.

REFERENCES

1. Torrance, K. E. and Sparrow, E. M. "Biangular Reflectance of an Electric Nonconductor as a Function of Wavelength and Surface Roughness." Journal of Heat Transfer, Vol. 87, Series C, 1965, pp. 283-292.

2. Torrance, K. E. and Sparrow, E. M. "Off-Specular Peaks in the Directional Distribution of Reflected Thermal Radiation." Journal of Heat Transfer, Vol. 88, Series C, 1966, pp. 223-230.

3. Torrance, K. E., Sparrow, E. M., and Birkebak, R. C. "Polarization, Directional Distribution, and Off-Specular Peak Phenomena in Light Reflected from Roughened Surfaces." Journal of Optical Society of America, Vol. 56, 1966, pp. 916-925.

4. Smith, A. M., Müller, P. R., Frost, W., and Hsia, Han M. "Super- and Subspecular Maxima in the Angular Distribution of Polarized Radiation Reflected from Roughened Dielectric Surfaces." AIAA Progress in Astronautics and Aeronautics: Heat Transfer and Spacecraft Thermal Control, Vol. 24, Edited by John W. Lucas, MIT Press, Cambridge, Mass., 1970, pp. 249-269.

5. Edwards, D. K., Nelson, K. E., Roddick, R. D. and Gier, J. T. "Basic Studies on the Use and Control of Solar Energy." Report No. 60-93, Department of Engineering, University of California, Los Angeles, Calif., Oct. 1960, p. I-5.

6. Breece, H. T., III, and Holmes, R. A. "Bidirectional Scattering Characteristics of Healthy Green Soybean and Corn Leaves in Vivo." Applied Optics, Vol. 10, 1971, pp. 119-127.

7. Müller, P. R. "Measurements of Refractive Index, Density, and Reflected Light Distributions for Carbon Dioxide and Water Cryodeposits and also Roughened Glass Surfaces." Ph. D. Dissertation, Department of Mechanical Engineering, 1969, University of Tennessee, Knoxville, Tenn.

8. Born, M. and Wolf, E. Principles of Optics. Third Edition, Pergamon Press, New York, 1965, p. 42.

9. Rense, W. A. "Polarization Studies of Light Diffusely Reflected from Ground and Etched Glass Surfaces." Journal of the Optical Society of America, Vol. 40, No. 1, Jan. 1950, pp. 55-59.

10. Christie, A. W. "The Luminous Directional Reflectance of Snow." Journal of the Optical Society of America, Vol. 43, No. 7, July 1953, pp. 621-622.

11. Voishvillo, N. A. "Reflection of Light by a Rough Glass Surface at Large Angles of Incidence of the Illuminating Beam." Optics and Spectroscopy, Vol. 22, No. 6, June 1967, pp. 517-520.

12. Beckmann, P. "Shadowing of Random Rough Surfaces." IEEE Transactions on Antennas and Propagation, Vol. AP-13, No. 3, May 1965, pp. 384-388.

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13. ABSTRACT

Bidirectional distribution measurements were made of the plane-polarized radiant flux transmitted through roughened glass samples having various surface roughnesses. These monochromatic measurements were made in the plane of incidence as a function of the irradiance zenith angle. For an irradiance angle of 0 deg, it is found that as the surface roughness-to-wavelength ratio increases the relative binormal transmittance of the glass decreases and the bidirectional transmission distributions become more diffusing but do not approach a Lambertian distribution. For off-normal irradiance angles and surface roughness-to-wavelength ratios significantly greater than unity, the maxima in the bidirectional transmission distributions of the roughened glass samples occur at zenith transmission angles smaller than those prescribed by the macroscopic application of Snell's refraction equation to a transmitting surface system. These transmission extrema have been termed anomalous refraction maxima and their angular displacement from the Snell direction is found to increase with increasing surface roughness and zenith incidence angle.

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